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APPLICATION OF OPTICAL FIBERS TO DNA'S TESTING PROGRAM

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15 October 1980

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Recent advances in the field of fiber optics communications and the development of fiber optic cabling systems represent a technological breakthrough that offers significant advantages over conventional coaxial cabling systems. The advantages of fiber optic systems include lightweight, wide bandwidth, freedom from electromagnetic interference (EMI) and groundloops, and immunity to crosstalk and short circuit loading. Different applications capitalize on those advantages most attractive to the user. The application

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of fiber optics to nuclear weapons effects tests sponsored by the Defense Nuclear Agency (DNA) is the topic of this report.

Since 1977, experiments utilizing fiber optics have been fielded in underground nuclear tests. Early applications involved experiments designed to characterize fibers in the underground testing environment. The success of these early measurements has developed confidence in fibers to the point of fielding non-redundant fiber optic links, thus, taking full advantage of their useful characteristics.

The encouraging results of testing fiber optic systems to date certainly justifies the continued interest in their use in underground nuclear testing and other applications involving severe environments. The all-dielectric construction of fiber cables makes them lightweight and eliminates many grounding and shielding problems. The wide bandwidth of the fibers enhances the multiplexing capabilities making it possible to reduce the total number of cables. This simplifies the cabling of an event and also has a significant economic impact.

In addition to benefitting UGT, advances in fiber optic technology can greatly impact other DNA activities such as hardening of military components and simulation and testing in high radiation environments. Using the UGT environment as a test bed, optical fibers can be characterized in severe radiation and stress environments. Due to the importance of optical fiber characteristics and the potential benefits from their use, it is recommended that DNA take a lead role in the research and development of fiber optic technology for use in adverse test and simulation environments.

PREFACE

The authors wish to thank Dr. George Sigel of the Naval Research Laboratory and Dr. Pete Lyons of the Los Alamos Scientific Laboratory for their comments and suggestions. The assistance provided by Mr. Noel Gantick of the DNA Field Command and our COR, Mr. R. C. Webb, is also gratefully acknowledged.

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SECTION 1

INTRODUCTION

The Defense Nuclear Agency (DNA) is charged by the Joint Chiefs of Staff with the responsibility to conduct nuclear weapons effects tests. These tests, conducted underground at the Nevada Test Site (NTS), demand sophisticated state-of-the-art systems designed to measure both the physical effects and the radiation output (diagnostics) of the nuclear device. Because of the hostile environment, the specialized nature of the source, and the large quantities of data required, many highly developed technologies often unique to this program, are needed to ensure a successful test. Further, advances in any of these technologies can have a significant impact upon the quality, quantity, and the economy of data collection and the ability to adequately quantify the measured effects.

Recent advances in the field of fiber optics communication (data transmission) represent a technological breakthrough which can offer significant advantages to underground testing (UGT). Data transmission from the experiments to the remotely located recording stations currently requires many runs of long lengths of metallic cables which present problems and limitations inherent with their use. The procurement and handling costs of these cables represent a significant fraction of the total cost of an underground test. The number of experiments and the bandwidth are severely limited by inherent metallic cable properties. Further, the logistics and reliability of grounding and shielding metallic cables in a high radiation background (both nuclear and electromagnetic) has long been a major problem in UGT programs.

Optical fiber technology offers substantial and fundamental advantages over conventional cables used for data communication systems. Several of these advantages are listed in Table 1. Different applications capitalize on those advantages most attractive to the user. Recent advances in the technology have been brought about by research efforts in support of the communications industry, principally the telephone companies. There, the lightweight and high bandwidth are particularly attractive.

For UGT, several of the advantages of fiber optics over metallic cables make their use attractive. The problems encountered in UGT due to the use of coax and other conventional cables can be lessened, if not eliminated, with the use of an all-dielectric, lightweight transmission link. The application of fiber optics to DNA sponsored UGT is the topic of this report.

An overview of a typical DNA-sponsored underground test is given in Section 2 where the requirements for data transmission and cabling are reviewed. In Section 3, fiber optic principles and characteristics are discussed. Section 4 is a summary of UGT measurements which have, to date, employed fiber optics. Demonstrated advantages of fiber optic waveguides for the UGT environment are given. Finally, in Section 5, areas are identified which should be explored in order to take maximum advantage of the capabilities provided by fiber optic technology in the UGT program.

Table 1. Advantages of fiber optics.

Wide Bandwidth
Freedom from Groundloops
Immune to Crosstalk
Freedom from Electromagnetic Interference (EMI)
Lightweight
Transmission Security
Immunity to Jamming
Immunity to Short Circuit Loading
Chemical Resistance
Use of Non-Strategic Materials

SECTION 2

CURRENT DNA EXPERIMENTS AND PRESENT CABLING REQUIREMENTS

Nuclear weapons effects are phenomena which are produced and given off by the explosion of a nuclear device and which interact with the surrounding environment or the materials to be exposed. The weapons effects normally consist of X-ray, gamma, and neutron radiations, as well as Electromagnetic Pulse (EMP), blast, and shock. The nuclear device is provided to the DNA by one of the weapons laboratories, i.e., the Lawrence Livermore Laboratory (LLL) or the Los Alamos Scientific Laboratory (LASL).

2-1 TYPES OF MEASUREMENTS.

While many types of measurements are taken during these tests, they can be divided into two broad categories: effects and diagnostic. Table 2 lists the various types of gauges that were fielded for a recent event, code named DIABLO HAWK (Ref. 1). The number of channels of each type of measurement is also given in the table. The required bandwidth for each type of measurement is given in Table 3. The strain measurements and most other effects measurements have relatively low frequency requirements (<20 kHz), while the diagnostic measurements require much higher bandwidth instrumentation systems (up to 1 GHz).

Table 2. Typical measurements made during an underground test.

Measurement Parameter	Number of Channels
Velocity	242
Acceleration	80
Strain	553
Stress	128
Break Wire	330
Make Wire	50
Sliffer	10
Pressure	421
Time Domain Reflectometer	2
Thermocouple	109
Impulse	32
Time Resolved Impulse	28
Time Resolved Momentum	16
Calorimeters	48
Carbon	15
Quartz	35
Compton Diodes	23
Photo Diodes	18
XRD	62
Current Sensors (EMP)	127
Total Channels	2329

Table 3. Typical UGT bandwidth requirements.

Measurement Parameter	Signal Frequency Range
Velocity	<20 KHz
Acceleration	<20 KHz
Strain	<20 KHz
Stress	<20 KHz
Break Wire	<20 KHz
Make Wire	<20 KHz
Sliffer	<20 KHz
Pressure	<20 KHz
Time Domain Reflectometer	< 5 MHz
Thermocouple	<20 KHz
Impulse	<40 KHz
Time Resolved Impulse	<50 MHz
Time Resolved Momentum	<50 MHz
Calorimeters	<50 MHz
Carbon	<50 MHz
Quartz	<50 MHz
Compton Diodes	<100 MHz
Photo Diodes	<100 MHz
XRD	<500 MHz
Current Sensors (EMP)	< 1 GHz

2-2 PHYSICAL LAYOUT OF EXPERIMENTS.

The layout for a typical, DNA sponsored underground effects test is shown in Figure 1. The tests are conducted in tunnels drilled into the side of Rainer Mesa at the NTS. The tunnels extend, horizontally, about one mile into the mesa at an overburden depth of 1000 to 1500 feet.

Pipes containing the experimental gauges are placed into drifts that extend from the nuclear device down the tunnel as far as 1000 feet. The pipes are designed to be gas tight and are evacuated during the test. Experiments are mounted on bulkheads placed across the pipe at several locations along its length. This provides several levels of radiation exposure. Signal cables from the individual experiments are routed behind the bulkheads and through the pipe walls at vacuum ports. From the vacuum ports, they go to instrumentation alcoves. These alcoves are generally located within 100 to 300 feet of the experimental station and are used for conditioning the data signals prior to transmitting them to the recording station. Recording stations are located both underground and at the mesa surface.

2-3 CABLING REQUIREMENTS.

Long lengths of cable are required for data transmission due to the remote monitoring of underground test measurements. Typical cable lengths from transducer to recording system can vary from 1000 to 5500 feet (Ref. 2). In all, more than 800 miles of cable can be used for instrumenting a typical event. More than half of the cable laid is not reused. For example, approximately 480 miles of cable, with procurement costs approaching $633,000 (Ref. 3) will be laid underground for use on the MINOR's IRON event planned for fall 1980.

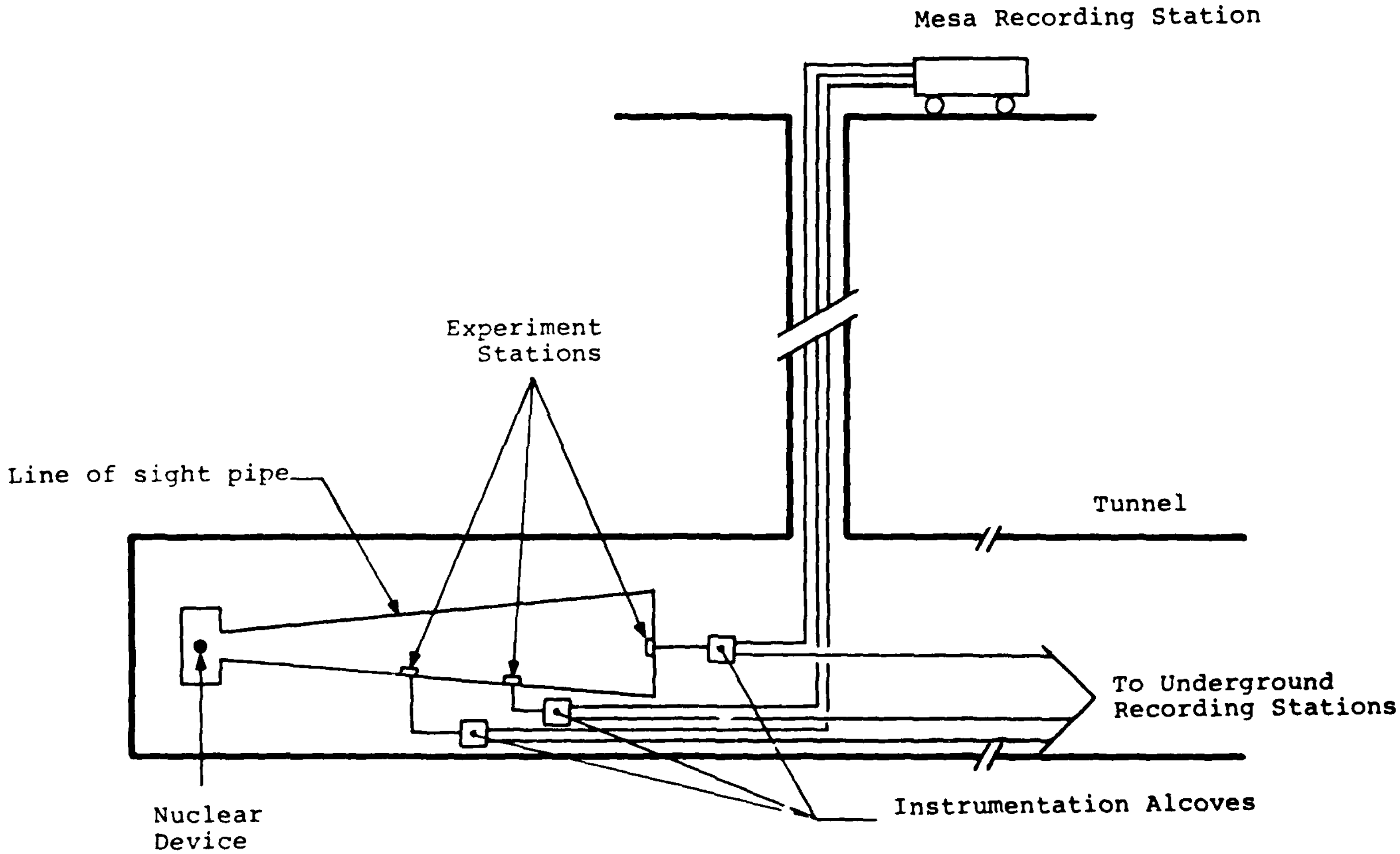

Figure 1. Layout of test tunnel at the Nevada Test Site. (Ref. 5)

Data transmitted to recording stations on the mesa surface are routed through the cable runs which are reused for each event. This link, then, limits the number of data channels which can be recorded uphole. Tests are performed on the cable plant before each event to determine which cables are usable. The listing shown in Table 4 gives the cables that were available in the main uphole cable plant for the DIABLO HAWK event (Ref. 1).

The type of cable utilized for each measurement is determined by several factors: signal requirements (frequency response, signal to noise ratio, etc), environmental parameters (radiation field, temperature, pressure, etc.), and grounding and shielding requirements for electromagnetic interference (EMI) suppression. Frequency response requirements for various gauges were given in Table 3. Environmental parameters vary along the length of the cable. For example, the radiation dose rates vary from approximately 10^{13} rad/sec (prompt gamma) at 3 meters from the source to background at the recording station (Ref. 4). Grounding and shielding requirements are overviewed in the following discussion.

2-3.1 Grounding and shielding requirements.

A major problem in fielding UGT experiments is the electrical overload and the consequent data loss from zero-time electrical noise in the measuring system. A model describing the zero-time noise identifies three sources that predominate (Ref. 5). These sources, illustrated in Figure 2, are outlined below:

1. - Photon induced surface emission of electrons for the experiment structure, pipe, and bulkhead.
2. - Photon induced charge transfer within the cables that are internal to the pipe.
3. - Induced noise in the cable system between transducer and recording system.

Table 4. Cables available in the uphole cable run for DIABLO HAWK (Ref. 1)

Cable Type	Number Available
Twisted Shielded Pair	1403
RG331	146
RG213	80
RG333	34
RG22B	20
RG215	20

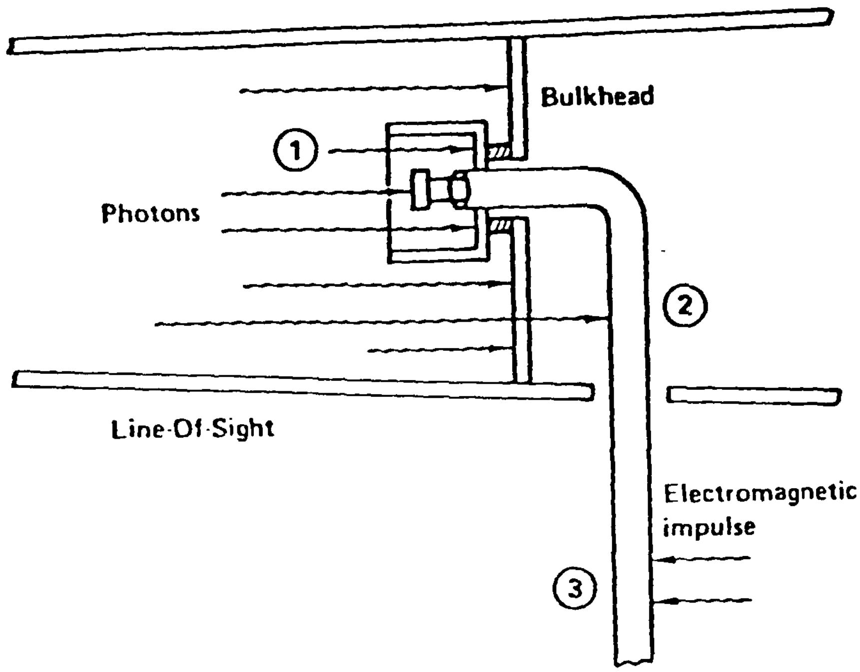

Figure 2. Zero-time noise sources.

Source number 3 is the most conventional and is present to some extent in any large cable system. It is, essentially, the impulse response of the cable plant.

Of great concern are the noise-induced signals that are allowed to propagate throughout the cable plant and couple into signal cables. There are several mechanisms that allow signals on the cable shields to penetrate into the cable. Cable conductors and splices are potential ports of entry for Radio Frequency (RF) noise. Also, braided cable shields leak electrically at frequencies above 100 MHz, with a coupling coefficient that is a function of the braid spacing. At lower frequencies, (i.e., less than 100 MHz), the cable shield is shallow compared to the skin depth of several millimeters. This allows signal coupling that is a function of the shield transfer impedance.

To overcome zero-time data loss, a large effort is put into grounding and shielding the instrumentation. Grounding and shielding requirements impose restrictions on cable selection and splicing, in addition to gauge design. Historically, experimenters have adopted systems based upon non-UGT recording environments as well as trial and error methods that have succeeded on previous tests. Recent efforts have been directed toward adopting a unified grounding and shielding plan to be followed by experimenters. (Ref. 4)

To insure against radioactive gas leakage to the atmosphere, gas blocks are installed in the cables used to transmit the data. For twisted shielded pair cable, such as might be used for low-level analog signals, gas blocks are constructed by separating the conductors and shields into individual wires and filling the area around the wires with epoxy. This results in a break in shield integrity and introduces a severe noise injection point for this type of cable.

In summary, a significant effort goes into planning the cabling for each underground test. The problems and limitations inherent in the use of bulky, metallic cables complicate the instrumentation of an event. These complications provide a tremendous incentive to develop all-dielectric, lightweight, data transmission links, such as those utilizing fiber optic waveguides. Recent developments, principles, and characteristics of optical fiber transmission links are discussed in the next section.

SECTION 3

FIBER OPTICS: PRINCIPLES AND CHARACTERISTICS

3-1 PRINCIPLES OF OPTICAL WAVEGUIDES

The theory governing optical waveguiding is derived from a straightforward application of Snell's Law. From this law of optics, the path of a ray of light can be determined in a refracting material from the following equation:

$$n_1 \sin\Theta_1 = n_2 \sin\Theta_2 \qquad (1)$$

The parameters are defined in Figure 3. The condition for optical waveguiding occurs whenever $\Theta_2 \geq 90°$, i.e. total internal reflection. This defines a critical angle of incidence, Θ_{1c}, necessary for total reflection given by:

$$\Theta_{1c} = \sin^{-1}\left(\frac{n_2}{n_1}\right) \qquad (2)$$

For $\Theta_1 < \Theta_{1c}$, the light ray will escape into the cladding. The principle of total internal reflection is utilized in light communications by constructing a cladded fiber with a core material having a larger index of refraction than the cladding material, i.e. $n_{core} > n_{clad}$, or in terms of the parameters defined in Figure 3, $n_1 > n_2$.

A characteristic parameter of optical fibers is the numerical aperture, NA. The NA is meant to serve as a measure of the light gathering ability of the fiber. Quantitatively, it is given by:

$$NA = \sin(\phi/2) \qquad (3)$$

The angle, $\phi/2$, (see Figure 3), is the maximum angle between the fiber axis and a light ray that will be guided along the fiber.

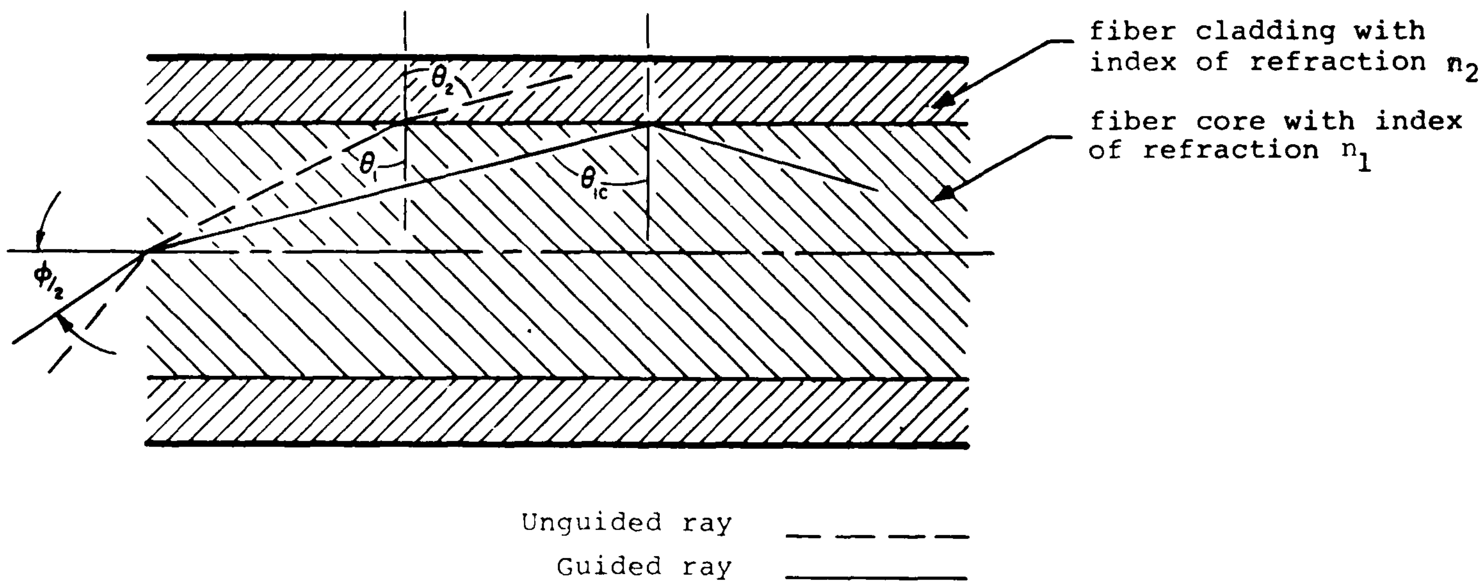

Figure 3. Guided and unguided rays of light in fiber optic waveguides.

The cone of light that will be accepted and guided along the fiber is characterized by the included angle, ø.

Propagating electromagnetic waves give rise to guided and unguided modes within the fiber. For any fiber waveguide of finite size, only a finite number of wave modes will be guided at a given optical frequency. Guided modes are the only ones of interest since they are confined by the fiber.

There are three broad categories of optical fibers:

1. Single Mode Step Index
2. Multimode Step Index
3. Multimode Graded Index

The three categories are illustrated qualitatively in Figure 4. In step index fibers, the index of refraction, n, is constant across the fiber core diameter, while in graded index fibers, n tapers continuously from the center axis value, n_1, to a lower value, n_2, at the end of the fiber radius.

Light paths for guided rays are illustrated in Figure 5. The single mode step index fiber has a small core diameter and a single mode is sustained. Larger diameter step index fibers allow more modes to be sustained. Since high angle rays travel a greater distance for a given length of fiber than lower angle ones, a pulse broadening occurs. A narrow pulse of light slowly broadens in time as it travels down the fiber, ultimately limiting the bandwidth of the fiber.

The advantage of the multimode fiber over the single mode is its larger numerical aperture. Multimode graded index fibers provide a means of utilizing this advantage and minimizing the pulse broadening. In this type of fiber, the smooth change in refractive index radially from the center of the fiber effectively decreases the path length difference between low and high order modes as

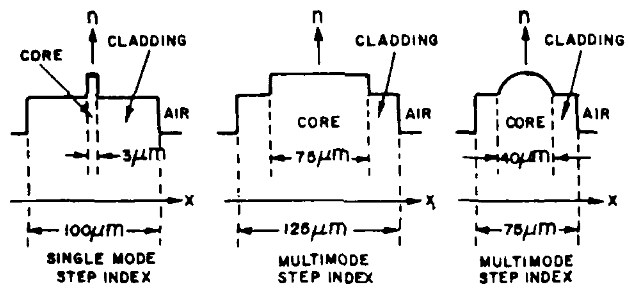

Figure 4. Refractive index profiles for three categories of optical fibers.

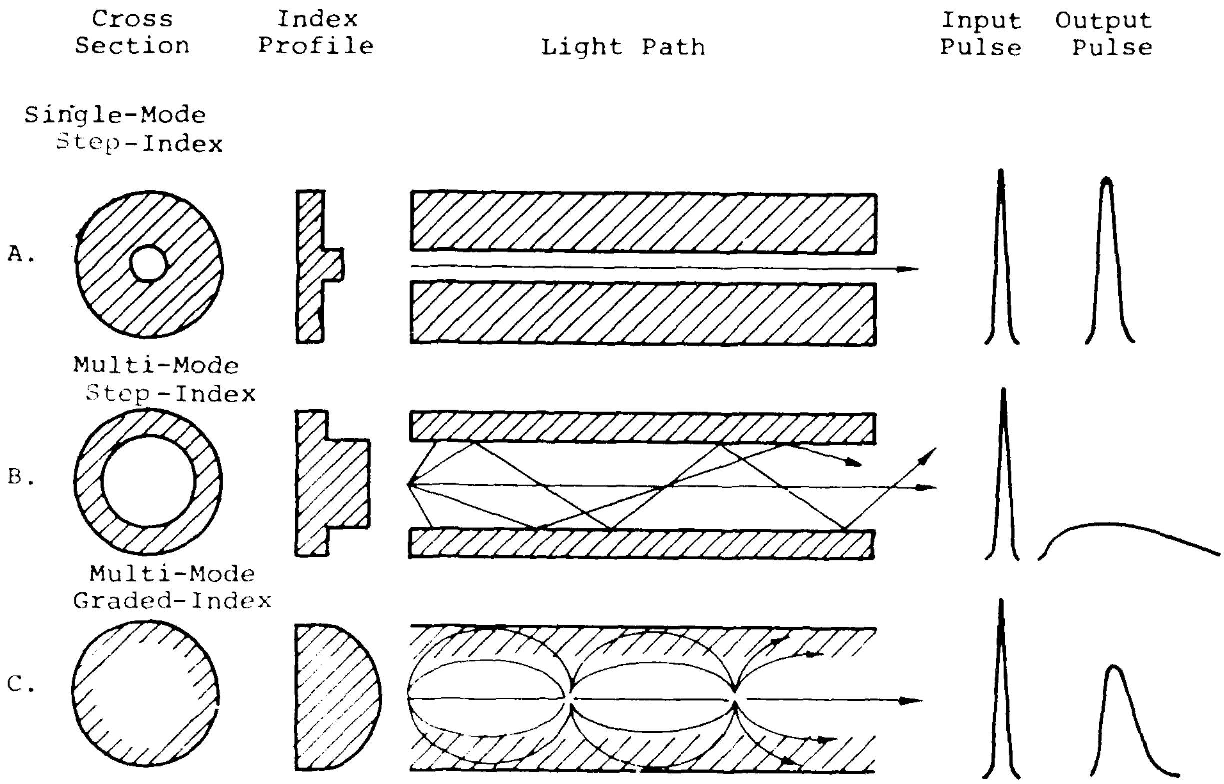

Figure 5. Modal distortion within optical fiber waveguides.

illustrated in Figure 5. In addition, the high angle rays now travel much of the time in a material with a lower index of refraction. As the index of refraction decreases, the velocity of propagation increases, decreasing the pulse spread even more.

3-2 FIBER CHARACTERISTICS.

3-2.1 Fiber Materials.

Four general classes of fibers are commercially available. The materials used and the method of preparation determine the mechanical and optical properties of the finished fiber. The general classes are described below.

3-2.1-1 Synthetic Silica Fibers. These all glass fibers are high purity and comprise the group with the lowest optical losses (attenuation). Some manufacturers dope the silica (SiO_2) cores and/or cladding with germanium (Ge), boron (B), phosphorous (P), or other material in order to obtain desired core/clad indices of refraction.

3-2.1.2 Polymer Clad Silica (PCS) Fibers. Glass fibers drawn from high purity synthetic silica rods are dip coated in a plastic or silicone solution and receive a thick protective polymer jacket to form a low cost, durable optical fiber waveguide. PCS fibers can support larger cores than all glass fibers without becoming brittle because of their plastic cladding. Since the cladding and core are made of dissimilar materials, however, PCS fibers are inherently step-index fibers.

3-2.1.3 Complex Silicate Glass Fibers. Virtually all of the early glass fiber optic waveguides were fabricated using lead silicate glass cores and borosilicate or soda-lime silicate glass cladding. The high index of refraction of the core, due to the presence of lead, results in a high numerical aperture and, therefore, very efficient coupling to a light source.

3-2.1.4 <u>All Plastic Fibers</u>. Fibers offering excellent mechanical properties near room temperature are fabricated from materials such as polymethylmethacrylate (PMMA) and polystyrene. These all plastic fibers do not suffer the brittle fracture problems of glasses, but exhibit the highest intrinsic optical losses of the four classes of fibers.

Several examples of each class of fibers are given in Table 5 along with manufacturers, characteristic loss properties, numerical aperature and bandwidth. Fibers are manufactured by a variety of techniques including chemical vapor deposition (CVD) processes, laser drawing processes, and compound melting. The processes and equipment used in fiber drawing can be found in the literature (Ref. 6, 7).

One or more optical fibers are incorporated into a cable structure for use in most systems. Cable structures provide environmental and mechanical protection, increased permissible tensile loading, and sizes convenient for handling. Examples of commercially available cables along with characteristic parameters and properties are listed in Table 6.

3-2.2 Mechanical Considerations.

The mechanical properties of the optical fiber cable can influence its ability to transmit optical information. Specifically, consideration must be given to the cable's strength and how tightly it can be bent in order not to degrade its signal handling capability.

3-2.2.1 <u>Minimum Bend Radius</u>. This is the smallest radius to which a cable is bent without placing the fiber under excessive mechanical stress. Bending the cable to a smaller radius causes coupling of an excessive number of propagating modes out of the core and into the cladding. In addition, stress cracks that actually shear the fiber

Table 5. Characteristics of commercially available fibers.

Core Material	Cladding Material	Manufacturer	Index Profile	Numerical Aperture	Bandwidth (MHz-Km)	Attenuation (db/Km @ λ in nm)	Price ($/m)
doped silica	silica	Fujikura Cable	single		10^4	.7 @ 1300	
silica	silica	Corning Glass Works	graded	.2	400	2 @ 900	1.40
silica	plastic	Maxlight Optical	step	.41	24	<5 @ 820	1.15
glass	glass	Optronic Fort	step	.29	30	10 @ 850	.95
glass	glass	Quartz and Silica	graded	.16	200	<15	
fused silica	plastic	Fiberoptic Cable	step	.25	25	20 @ 820	.90
silica	silicone	Quartz Prod/Q & S	step	.38	15	50 @ 820	1.50
glass	glass	Optronic Fort	step	.48	20	100 @ 850	.15
plastic	plastic	Optronic Fort	step	.5	10	400 @ 850	.60
acrylic	fluorocarbons	Poly-Optical Prods.	step	.5		900	.02

Table 6. Characteristics of commercially available fiber optic cables.

Manufacturer	Number of Fibers	Cable dia. (mm)	Weight (kg/km)	Tensile Strength (kg)	Min. Bend Radius (cm)	Bandwidth (MHz-Km)	Attenuation (dB/km @ λ in nm)
Fujikura Cable	1-48	3-30	10-500	50-300	5-36	10^4	1.0 @ 1300
Optronics Fort	4	12		70	20	300	4
Times Fiber Comm.	1-12					200-600	5 to 8
Belden	6	8	40	140	10	20	5 @ 850
Maxlight Optical	1	2.4	6	80	.5	24	<10 @ 630
Optelecom	3	3.5	21	200	10	20	15 @ 800
MERET	1	.6	6	30		50	100 @ 900
Siecor	6	5.0	25	750	2.5	200	20

and break the link are induced.

3-2.2.2 <u>Tensile Strength</u>. Tensile strength is especially important if the cable must be drawn through conduit or hang self-supported over long distances. Fiber optic cables always have some additional members that provide the strength needed in most applications. Most often they are made of dielectric material such as Kevlar which also maintains electrical isolation. Thus, it is the strength of these additional members that actually handles the tensile load.

3-2.2.3 <u>Microbending</u>. A significant factor in optical cable design is the optical loss caused by a phenomenon called microbending. When an optical fiber is deformed on a microscopic scale, coupling of propagating modes from the core to the clad becomes a problem. To overcome this, buffering of the fibers is accomplished either before or during cable manufacture.

An example of a ruggedized cable suitable for a variety of demanding applications is SIECOR General Purpose optical cable* manufactured by SIECOR Optical Cables, Inc. A cross-section of the SIECOR cable is shown in Figure 6 (Ref. 8).

3-2.3 Optical Properties.

The optical properties of importance in fiber optic waveguides are attenuation and distortion. Both impact on the usable length of the fiber and on the bandwidth of the system. The influence of other components of the fiber optic system on these two properties is discussed in Section 3-3.

3-2.3.1 <u>Attenuation</u>. The two main sources of loss in the optical waveguide are scattering and absorption. Typical attenuation loss from a high silica optical fiber without dopants, as a function of wavelength, is shown in Figure 7. The absorption bands which appear at 0.63, 0.73, 0.87, and 0.95 μm result from hydroxyl absorptions in

*Note: Mention of a product does not indicate endorsement of that product by DNA or Geo-Centers, Inc.

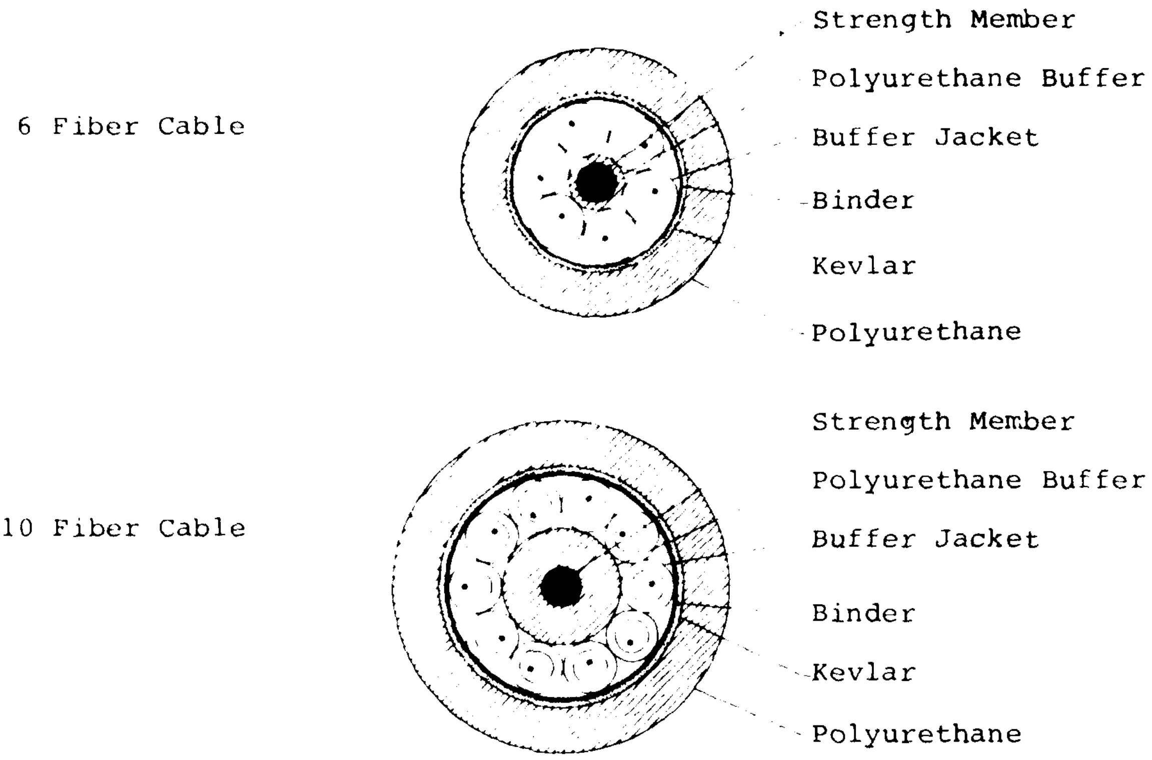

Figure 6. Cross section of SIECOR cable.

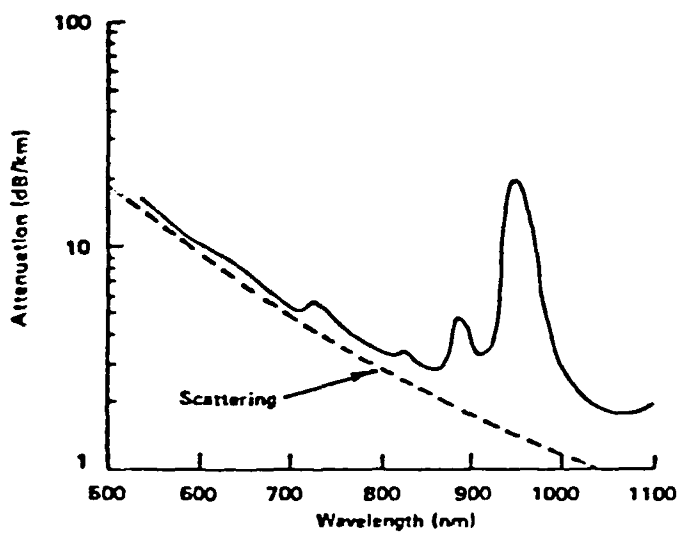

Figure 7. Typical attenuation loss from a high silica optical fiber without dopants.

the glass. Dopants or impurities, if present in the glass, would provide additional absorptions contributing to increased loss. Impurity levels of the order of one part per billion of copper, iron, or chromium, for example, can result in additional loss of one decibel per kilometer (db/km).

Scattering losses in the guide arise from intrinsic material fluctuations. Even in the absence of inclusions or defects which can cause light scattering (and hence loss), the fiber will display an intrinsic scattering caused by density fluctuations, i.e., Rayleigh scattering. These fluctuations in density are thermal in origin and frozen into the bulk glass at high temperature. Of the scattering losses, this probably represents the ultimate lower limit to attenuation (Ref. 9). The dashed curve in Figure 7 shows the intrinsic attenuation contribution from Rayleigh scattering.

Attenuation of optical fibers and cables is customarily expressed in decibels and is normalized to a one kilometer reference length. Thus, from powers transmitted (P_t) and received (P_r) over a length of L kilometers:

$$\text{Attenuation} = \frac{-10 \log (P_r/P_t)}{L} \text{ (db/km)} \qquad (4)$$

3-2.3.2 Distortion. The bandwidth of optical fibers is limited by a mechanism different from that which limits the bandwidth in a coaxial cable. Attenuation and bandwidth of conventional coaxial cables are closely related because the loss is a function of frequency. This is not true for optical fibers. The characteristics of coaxial cables and optical fibers are compared in Figure 8.

In an optical waveguide, bandwidth is limited by two factors: modal distortion and material dispersion. Modal distortion refers to the broadening of pulses being transmitted through a given fiber caused by different modes arriving at the detector at different

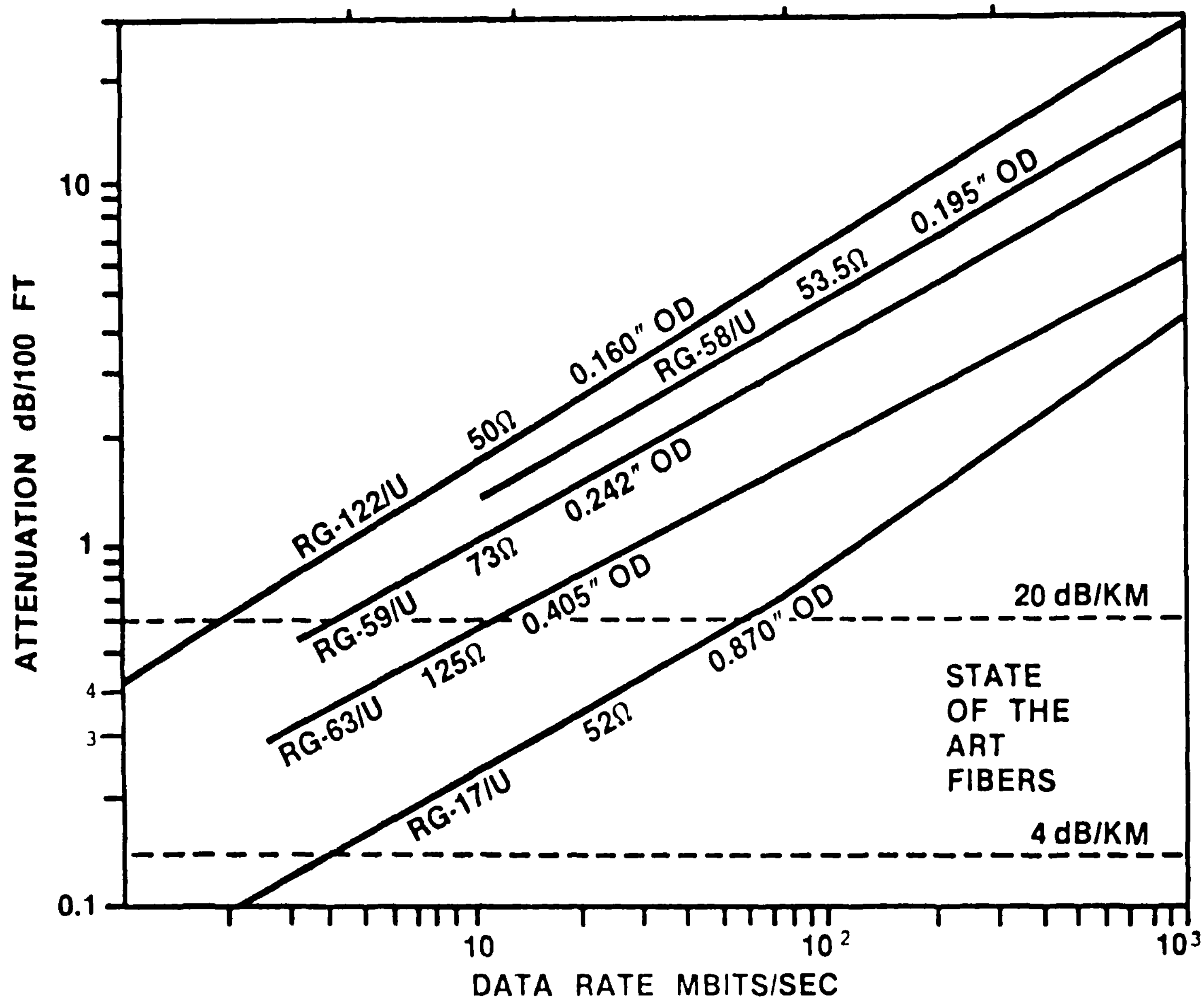

Figure 8. Comparison of coaxial cable and fiber optic attenuation.

times. As mentioned previously, a graded index profile minimizes this limiting factor for a multimode fiber.

Material dispersion is attributable to the wavelength dependence of the refractive index of the material used to form the waveguide. For silica, this dependence has a minimum near 1300 nm. The exact wavelength of the minimum is influenced by the additives and impurities present in the silica core materials. These additives and impurities can give rise to absorption bands which influence the location and absolute value of the intrinsic loss minimum. For a particular application, the significance of the material dispersion depends on the spectral width of the source.

3-2.4 Radiation sensitivity.

The effects of ionizing radiation on optical fiber waveguides are normally subdivided into two broad regimes: transient effects and permanent effects. Transient effects include luminescence and attenuation. Luminescence is most intense in the short wavelength region of the spectrum. Radiation-induced absorption is also generally greatest in this region; thus, the short wavelength component becomes self-absorbed. Appropriate filtering is used to further remove the radiation induced luminescence. The addition of dopants such as Ge, B and P also serves to reduce the luminescence output of the fiber.

Permanent damage due to ionizing radiation and neutrons takes the form of density changes and attenuation. Density changes result in changes in the index of refraction of the glass and may lead to loss of waveguiding in the fibers. Also, the effects of density changes on bandwidth represent a serious, long-term problem for fibers in radiation environments. This results from the sensitivity of the pulse distortion to the index profile of graded index waveguides. Other permanent damage includes changes in the mechanical properties of the fibers.

Table 7 lists the key parameters in the radiation damage of fibers. Results of radiation damage studies can be found in the literature (Ref. 10, 11). Figures 9 and 10 summarize some of the radiation damage results (Ref. 10). Figure 9 shows the total loss sustained in fibers of different composition as a function of gamma ray dose from steady state ^{60}Co irradiation. The transient response of some of these same fibers to pulsed energetic electrons is illustrated in Figure 10. As can be seen from Figure 10, significant recovery can occur following a dose of transient radiation.

From the figures, therefore, it can be seen that the radiation induced effects can be minimized by proper selection of the fiber material. All of the parameters listed in Table 7 must be considered when selecting a fiber for a specific application. For example, temperature has been shown to significantly influence the recovery of the radiation induced attenuation of the optical fiber waveguide. Table 8, taken from reference 10, lists system requirements and suggests candidate classes of fibers for some applications involving nuclear environments. The actual choice of fiber, will, of course, depend upon the system architecture, attenuation, and bandwidth requirements.

3-3 FIBER OPTICS SYSTEMS

Systems employing optical fiber waveguides can be active or passive in nature. Active systems utilize electro-optic converters which take an electrical output from a conventional detector and convert it to an optical analog for transmission over a fiber optic link. This type of system essentially replaces a standard wire link, benefitting from the advantages of fiber cables. The passive system omits the intermediate electrical step and requires a direct radiation to light converter. While fundamentally simpler, passive systems require detector development for many applications. The following systems discussion deals with the active type of system. Passive systems are discussed briefly in the next section.

Table 7. Key parameters in the radiation damage of fibers.

A. Radiation Parameters

1. Total Dose
2. Time After Irradiation
3. Dose Rate
4. Type of Radiation (gamma, neutrons, electrons, etc.)
5. Energy

B. Fiber Parameters

1. Wavelength
2. Temperature
3. Injection Conditions
4. Light Intensity
5. Luminescence
6. Radiation History

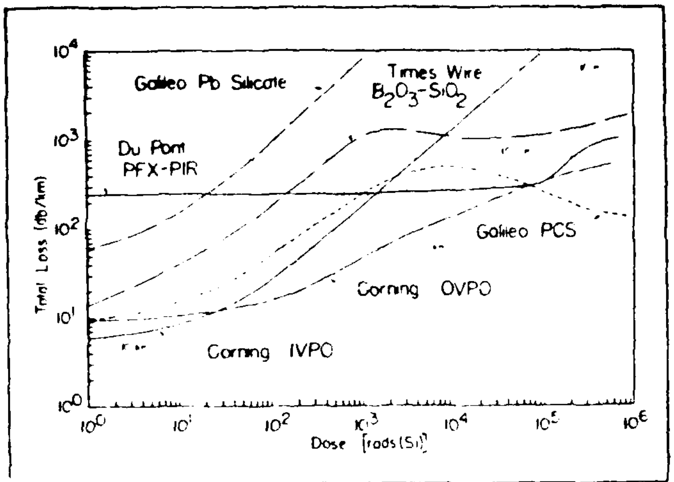

Figure 9 Total loss in optical fiber waveguides as a function of dose during in situ steady state ^{60}Co *irradiation.*

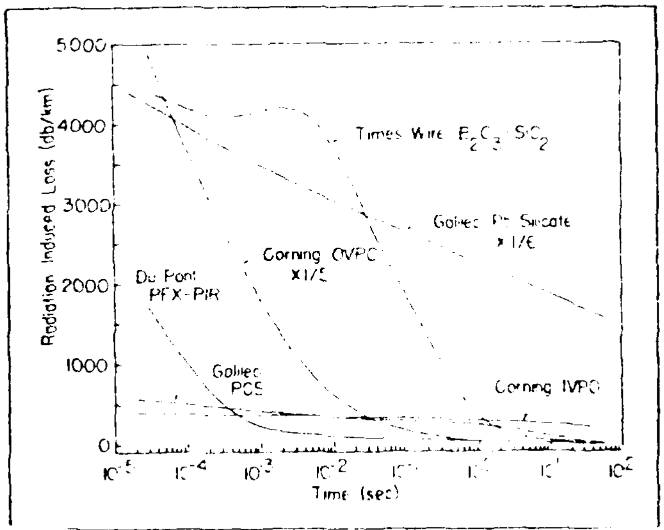

Figure 10 Decay of radiation-induced optical attenuation following a dose of electrons.

Table 8. System requirements, fiber behavior, and candidate fibers for optical communication systems in nuclear environments.

System Requirements	Fiber Behavior	Candidates*
1. Minimum downtime	Minimum transient absorption	
High total dose (unmanned-missile, satellite)		SiO_2 core (PCS, all glass)
Moderate total dose (manned-aircraft, ground links)		SiO_2 core, Ge-P doped silica core
2. Low to moderate dose rate, 1 sec downtime (manned-fallout, reactor environs, space ambient)	Good long term recovery	SiO_2 core, Ge-doped silica core w/o P, Silicate + Ce, Plastic
3. Neutron flux (weapons, reactor)	B-free core & cladding	SiO_2 core (F-doped silica or polymer clad). binary Ge-doped silica core--SiO_2 clad

* Choice depends upon system architecture, attenuation and bandwidth requirements.

3-3.1 Active System Design.

A block diagram of an optical link is shown in Figure 11. The design considerations of such a link must include distance, information rate (bandwidth), modulation method, and interfacing.

Three factors influence the distance over which a link can propagate information: source power, losses in the fiber and at the coupling points, and the receiver sensitivity. Sources used in most links are either injection diode lasers or incoherent light emitting diodes (LEDs). Table 9 lists several commercially available transmitters along with some useful characteristics. While diode lasers can launch more power into the fiber, LEDs are less expensive and usually more rugged and durable. Also, LED drive circuits are not as complex as those required for lasers.

Table 10 lists several commercially available receivers along with some useful characteristics. Silicon is used almost exclusively for wavelengths less than 1.0 μm. Current transmitter/receiver research is concentrating on long wavelength (> 1.0μm) devices. Silicon detectors are not suited for wavelengths longer than 1.1 μm; thus, receiver development requires a material suitable for these wavelengths. Compounds of doped gallium arsenide (GaAs) are currently used for receivers and transmitters in this long wavelength region. Table 11 lists some of the source and detector materials available for use.

The incentive for the development of these "second generation" (i.e., long wavelength) fiber optic systems is due in part to the lower optical attenuation of the fibers at approximately 1.3 μm. Figure 12 illustrates the intrinsic loss of a typical low loss silica fiber used for long wavelength operations (Ref. 12). The loss that is acceptable for a particular application depends on the system design.

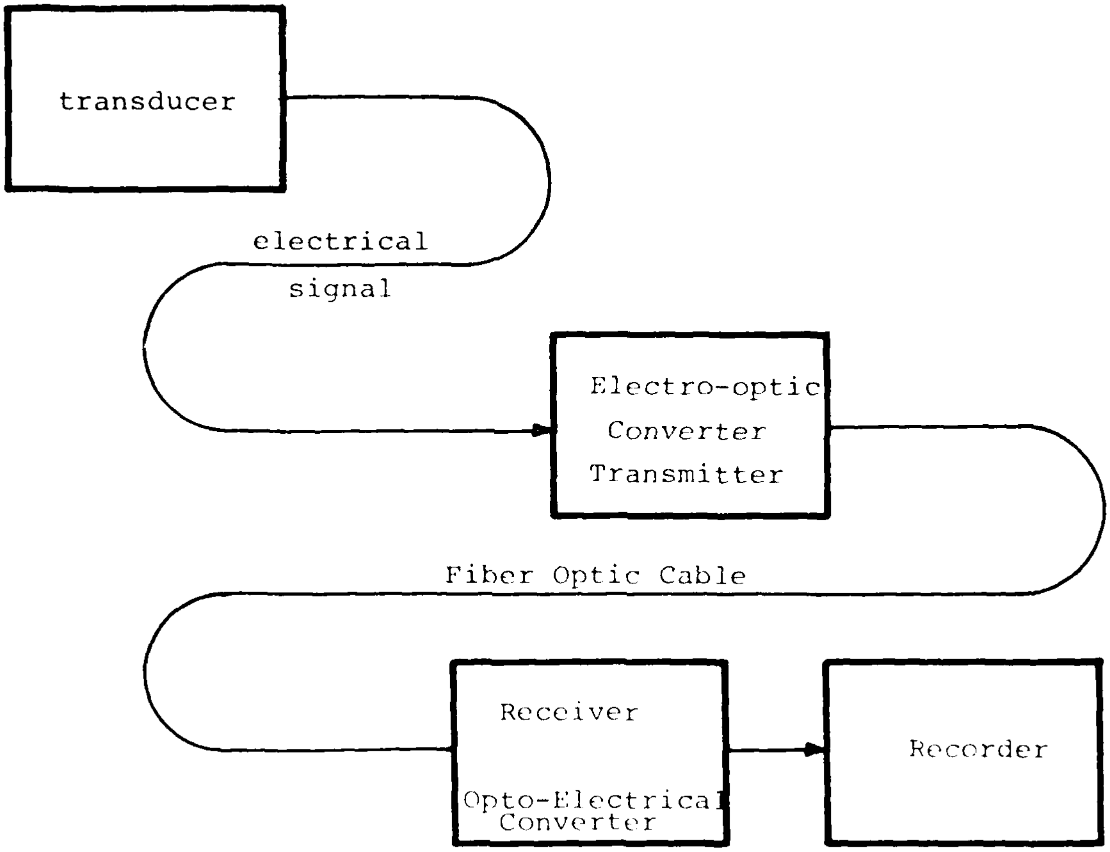

Figure 11. Block diagram of an optical transmission link.

Table 9. Commercially available optical transmitters.

ANALOG TRANSMITTERS

Wave length(s) (μm)	Source Type	Bandwidth (MHz)	Peak Power (μw)	Power Requirements (v @ ma)	Rise time (ns)	Manufacturer	Price ($)
660	LED	3.5	35	± 12 or 15 ac		Math Associates	195.
850	LED	8	20	± 15	50	Compagnie Lyonnaise	1350.
900	GaAs		140	1.6 @ 100	25	Motorola Semiconductor	40.

DIGITAL TRANSMITTERS

Wave length(s) (μm)	Source Type	Bit Rate (Mb/s)	Peak Power (μw)	Power Requirements (v @ ma)	Rise time (ns)	Manufacturer	Price ($)
660	LED	2	35	7 or 12 ac	150	Math Associates	158.
820	LED	2	70	+ 5 @ 230	25	Canoga Data Systems	240.
840	Laser diode	34	1,000	± 12 v	1	Thomson CSF, LTT	
850	Laser	.0096	100	230	10^6	Standard Telephone	
900	LED	30	20	5 @ 160	15	Electro Optic Dev	600.

Table 10. Commercially available optical receivers.

ANALOG RECEIVERS

Wave length(s) (μm)	Detector type	Bandwidth (MHz)	Power Requirements (v @ ma)	Signal to noise ratio	Linearity	Manufacturer	Price ($)
600	pin	3.5			>1%	Math Associates	235.
850	APD	8	230 ac	40		Standard Telephone	
900	APD	200	15 @ 70	40	3%	Electro Optic Day	1,200.
905	pin	DC-1	12 @ 6			MERET	135.

DIGITAL RECEIVERS

Wave length(s) (μm)	Detector type	Bit Rate (Mb/s)	Power Requirements (v @ ma)	Bit Error Rate	Compatability	Manufacturer	Price ($)
660, 890	pin	.1			TTL	Math Associates	100.
820	pin	2	5 @ 140	10^{-9}	TTL	Canoga Data Systems	240.
850	pin	0-2	± 15	10^{-8}	TTL	Compagnie Lyonnaise	600.
905	pin	1	± 12	10^{-12}	TTL	MERET	370.

Table 11. Long wavelength source and detector materials.

Sources

Type	Applicable Wavelength
GaAlAs	0.84 μm
AlGaAsSb/GaSb	1.2 to 1.8 μm
InGaAsP/InP	1 to 1.6 μm

Detectors

Type		Applicable Wavelength
Si	PIN	Up to 1.1 μm
	APD (Avalanche Photo-Diode)	
InGaAs	APD	1 to 1.7 μm
Ge	APD	Up to 2.0 μm
CdS/CuInSe	PIN	Up to 1.3 μm
InGaAsP/InP	APD	1 to 1.6 μ
AlGaAsSb/GaSb	APD	1.2 to 1.8 μm

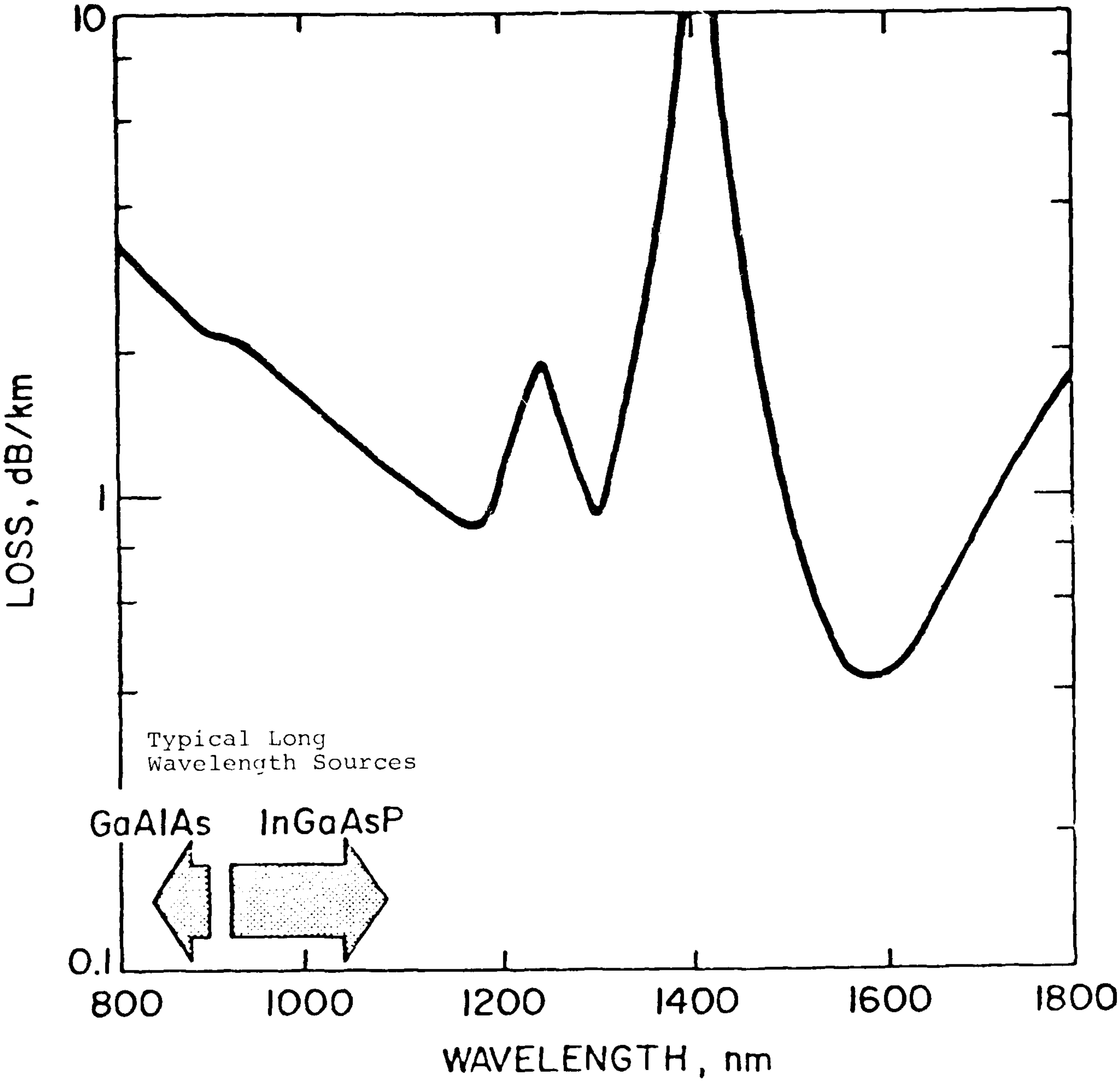

Figure 12. Loss spectra of fibers for long wavelength operation.

The difference between the power level of the transmitter and the required power level at the receiver for a given signal to noise ratio is termed "the budget". The budget is dependent on the bandwidth required. In the case of digital information, this is the bit rate. Budget as a function of bit rate is illustrated in Figure 13. The band termed "digital message" in the figure indicates the range of typical receiver sensitivities; the two upper bands are representative of the ability of the lasers and LEDs to couple power into the fiber. For a given bit rate, the difference, in decibels normalized to 1 milliwatt input power (dBm), between the digital message band and the appropriate source band yields the budget. For example, a LED system operating at 100 Megabits/sec allows for approximately 30 dBm of optical signal attenuation between source and detector. Besides attenuation from the fiber, losses in the connectors and splices, which often dominate the loss terms, also account for the "spending" of the allowed budget.

Optical fiber bandwidth is generally expressed as a bandwidth-distance product. As mentioned previously, bandwidth is limited principally by two factors: modal distortion and material dispersion. Laser systems operating with single mode fibers avoid multi-mode effects, but in the case of LED systems, multi-mode fibers must be used in order to collect enough light from the LED. For good multi-mode fibers, however, the bandwidth distance product caused by residual mode delay differences exceeds 1 GHz-km.

Figure 14 shows the range of bandwidth-distance products for typical InGaAsP LEDs and germanium-doped silica multi-mode fibers having a numerical aperture of 0.2. Also, the bandwidth-distance product for a semiconductor laser, single mode fiber system is shown in the figure. As can be seen, bandwidth-distance products near or exceeding 1 GHz-km can be achieved with systems operating at approximately 1.3 to 1.4 μm.

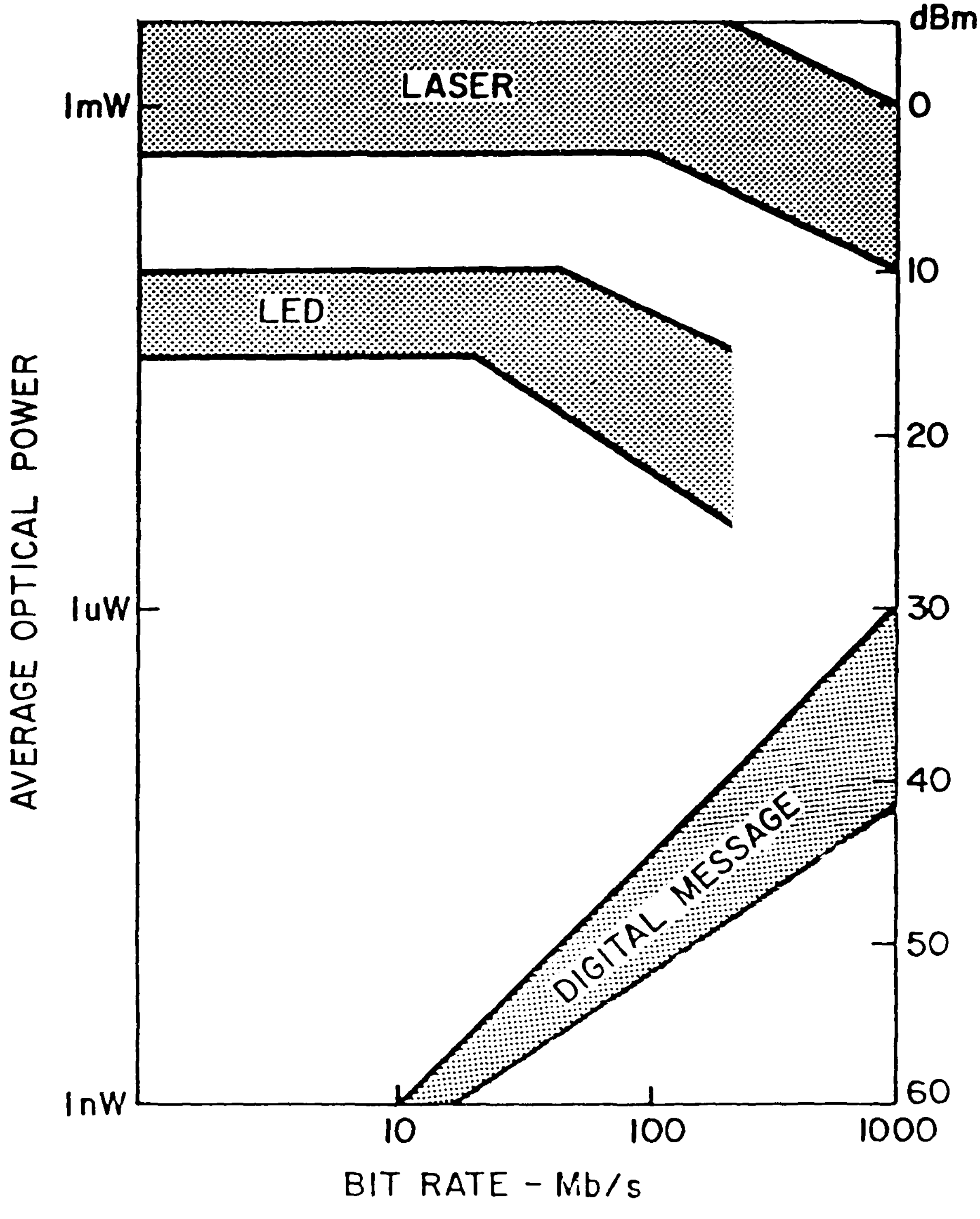

Figure 13. Loss budget for fiber transmission links. (Ref. 12)

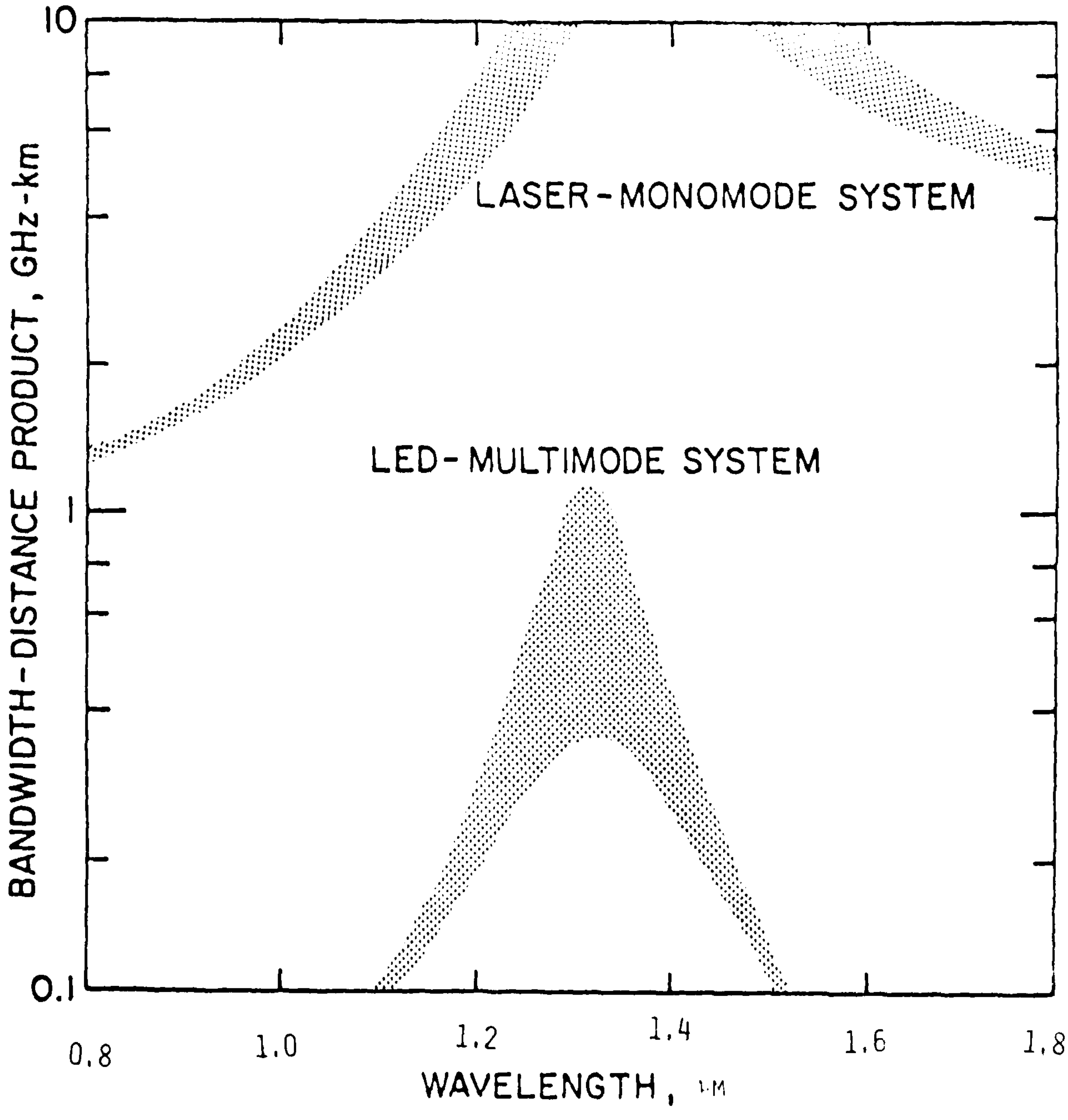

Figure 14. Range of bandwidth-distance products. (Ref. 12)

Modulation of the sources can be either analog or digital. The selection of the modulation method depends upon several factors including the initial format of the information to be transmitted, distance, and desired interface simplicity. With digital modulation, the emitting source is driven to one of only a few discrete levels (usually 2) and the information to be transmitted is coded.

SECTION 4

USE OF FIBERS IN UGT

The cabling requirements for an underground nuclear test have been briefly described. Considerable engineering development has gone into solving the cabling problems which complicate the fielding of remotely monitored measurements. For example, in order to avoid zero-time noise and subsequent loss of data, a large effort has been expended on the proper grounding and shielding of the cable runs.

The advantages of fiber optics, as discussed in Section 3, have been utilized in underground nuclear testing. In this application, the bandwidth, freedom from EMI, low cost, and lightweight can all be of significant advantage. Since 1977, UGT experiments utilizing fiber optics have been fielded at the NTS (Ref. 13). Early applications involved experiments for characterizing fibers in the UGT environment. The success of these early measurements has developed confidence in fibers to the point of fielding non-redundant fiber optic links taking full advantage of their useful characteristics. The advantages of fibers as applied to UGT are discussed in this section, and some of the work involving fiber optics at the NTS is reviewed.

4-1. ADVANTAGES OF FIBERS FOR UGT.

Several advantages can be realized by utilizing fiber optics in UGT applications. Table 12 compares the 3 dB frequency response, procurement costs, and weights for one kilometer lengths of SIECOR cable and a high quality coax cable. As mentioned in Section 3, the SIECOR cable is a six or ten fiber bundle. The large bandwidth of optical fibers presents a major advantage for this type of transmission

Table 12. Comparison of high quality coax cable and SIECOR optical fiber cable.

	Bandpass	Procurement Cost	Weight
RG 331	1.3 MHz	$1840.00	220 kg
SIECOR 6 fiber	200 MHz	$1400.00* per fiber	46 kg
10 fiber	200 MHz	$1230.00 per fiber	66 kg

*Cost comparisons to coax should include cost of transmitter and receiver (see text).

link over a conventional metallic cable. Comparing the optical fiber bandwidth with the typical UGT measurement requirements (Table 3) illustrates that the capability of the fiber is severely underutilized if each measurement channel is transmitted on its own fiber. The advantage of the fiber is the enhanced multiplexing capabilities it affords the user. Transmitting multiple data channels along the same transmission line provides cost savings (both procurement and installation), installation time savings, and helps simplify the grounding and shielding effort.

Cost comparisons between fiber optic and coaxial cable links should include the cost of the transmitter and receiver required for the fiber link. If the multiplexing capabilities afforded by the fiber cable are not taken advantage of, (i.e., direct channel for channel replacement of the coax cable), each fiber channel will require a transmitter and receiver. Referring to Table 9, the current costs (1980) of representative transmitters range from approximately $200 to $500; from Table 10, receiver costs range from approximately $100 to $600. (It should be noted that current fiber and component costs are decreasing.) From these examples and the procurement cost comparison given in Table 13, it is seen that even with a direct channel for channel replacement of high quality coax links with fibers, the fiber links are procurement cost competitive.

For the total cost picture, installation costs must be considered. The bulky coaxial cables incur handling costs approximately equal to their procurement costs (Ref. 13). The lightweight fiber cables, where several channels are installed per cable, reduce these costs significantly. Cable savings provided by the enhanced multiplexing capabilities assures an even greater cost benefit with fiber links. For example, a system designed for an upcoming event replaces up to 92 twisted, shielded pair links with a single fiber bundle (Ref. 18).

Another advantage of fibers lies in the fact that all-dielectric data transmission links become possible with fiber optic cables. Any reduction in the ground plane available for EMI induced noise propagation goes a long way in simplifying the grounding and shielding requirements. Resultant decreases in or elimination of zero-time noise allow much more reliable data recovery in the micro-second time regime. Also, the non-metallic cables help minimize signal coupling between experiments, i.e., cross-talk.

Many of the disadvantages anticipated with the use of fiber optic cables did not materialize during field use. As discussed in the next section, the fiber cables have proven to be surprisingly rugged in field applications, and current engineering developments have yielded splice losses in cables of less than 1 dB/km (Ref. 14). Cable requirements unique to underground nuclear tests have been met with minimal compromise of the optical and mechanical properties of the fibers.

4-2. DIAGNOSTIC APPLICATIONS.

In addition to DNA, the Department of Energy (DOE) also sponsors underground nuclear tests. Many of the experiments fielded in support of a DOE-sponsored event are of the diagnostic type. These tests are usually conducted at the bottom of deep holes rather than in tunnels as is typical of most DNA-sponsored events (Ref. 15). Hole depths vary from 200 to 1000 meters; hole diameters range from 90 to 225 cm. A cylindrical steel rack, up to 70 meters long, houses the nuclear device and the experiments which are mounted at distances varying from 50 cm to the length of the rack from the device.

The operation of lowering the rack to the bottom of the hole and the procedure followed to fill and plug the hole require that the cables connecting the experiments with the recorders located uphole withstand severe mechanical stresses. Since the hole is completely filled with layers of sand, gravel, and epoxy, the cables are exposed to these materials over long distances. A schematic of a typical rack geometry (for a DOE event) is shown in Figure 15.

The first application of fiber optics to UGT examined the feasibility of fiber optics use in the NTS environment (Ref. 13). For this first test, tools and capabilities had to be developed. Radiation induced luminescence and absorption were measured for two types of exposed fibers. These data were then transmitted to recording stations along 700 meters of continuous CORGUIDE cable. A passive fiber optic system was thus formed.

Gas blocking of the CORGUIDE cable was accomplished by compressing a 10 cm length of cable in a specially shaped block under increased temperature and pressure. All leak paths, except the strength member, were thus sealed. The outer jacket of the cable was scraped away just outside the block and this area was potted with epoxy which wicked into the stranded Kevlar. After perfection, a gas block, field installed using this technique, resulted in optical losses less than 0.2 dB.

The results of the first field test provided radiation effects data for fibers and demonstrated the feasibility of using fiber optic cables for data transmission in the UGT environment. Subsequent work utilizing fiber optics systems for UGT diagnostics has incorporated radiation to light converters for gamma and neutron detection (Ref. 16).

In one system, a Cerenkov converter was used to detect gamma rays. A fused silica converter, actually a PCS fiber, was used for the transducer. The data were transmitted to the recording stations over fiber cables. Filters were used to limit material dispersion by narrowing the optical bandpass to 1 or 2 nm around the 800 nm wavelength chosen for data transmission. The system was then able

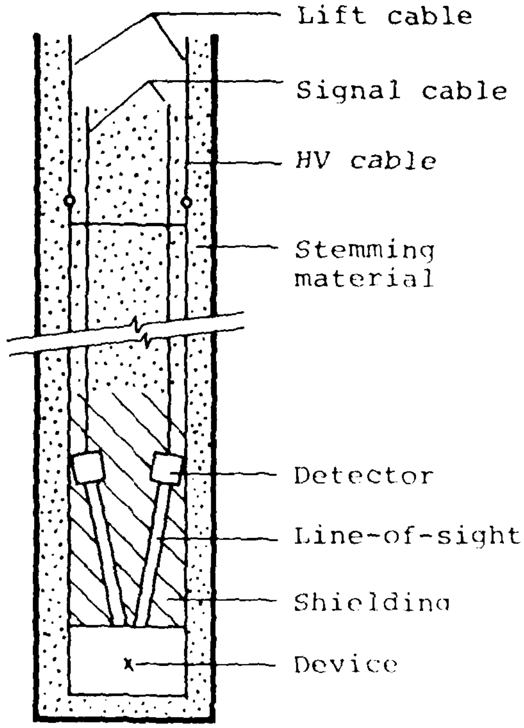

Figure 15. Schematic of a typical NTS rack geometry.

to approach a 1 GHz bandwidth.

A second system that has been successfully fielded provides space and time resolved neutron imaging. The signals from liquid scintillators, arranged in a close packed array, are transmitted along fiber cables to uphole recording stations. Six meters of PCS fiber, which has good radiation resistance but relatively poor bandwidth capability, connected the detector array to the graded index fiber transmission line. This helped limit the radiation induced transient response while still providing the required bandwidth.

Fiber cables from three vendors were utilized. All vendors provided gas tight cables able to pass the gas block requirements. Strength members incorporated into the cable were non-metallic providing an all-dielectric transmission link. In both the gamma and neutron system, the fiber cables proved to be surprisingly rugged with no special handling required. In several instances, the uphole portion of the cable has been retrieved without any measurable degradation in any property.

4-3. EFFECTS MEASUREMENT APPLICATIONS.

In Section 2, examples of effects measurements taken during an underground test were given. Transducers currently used in this application require bias voltage and provide electrical signals representing the parameter of interest. Without extensive transducer development, then, these systems lend themselves more readily to the use of active fiber optic links. All of the advantages of the fiber optic cables are still realized (e.g., cost, EMI immunity, etc.). The results of an application of a fiber optics link to a strain gauge channel fielded during a DNA sponsored underground test are given in this section.

Strain is mathematically defined as the change in length divided by the original length. Since even the most rigorous and complex analytical methods of determining strain in a loaded body are only approximate, measurements under realistic loading conditions are necessary for an optimum mechanical design of a system. Strain gauge data have, at times, been incomprehensible due to failures and grounding and shielding problems. Great care must be exercised when fielding strain gauges if noise-free, usable, signals are to be recorded.

Several types of strain gauges are fielded during a typical UGT. The principle of operation for wire and foil gauges involves the change in resistivity that accompanies dimensional changes in conductors. In a typical wire strain gauge, a wire about 10-12 cm in length and 0.0025 cm in diameter is formed into a grid shape and bonded to the surface to be tested. Foil gauges are made by printing the desired pattern on a thin sheet of metal alloy foil with an acid-resistant ink, then etching away the imprinted portion. Any strain in the surface will be transmitted to the conductor, with a corresponding change in resistance producing a measurable output. The change in resistivity is usually measured by placing the gauge in a bridge configuration as shown in Figure 16.

For the first test of fiber optics in this application, a fiber link from the instrumentation alcove to an underground recording shack was run in parallel to a coaxial cable link (Ref. 17). The data from the foil strain gauges were transmitted along both links. Standard FM multiplex techniques were utilized in the instrumentation alcove. LEDs and PIN diodes were chosen for the transmitter/receiver combination. The specifications of the fiber optics link included: bandwidth-8MHz, dynamic range-40 dB.

Data transmitted on the coaxial cable link from one of the foil strain gauges are shown in Figure 17. The two large "spikes" occurring prior to 400 microseconds are caused by cable plant ringing and make it impossible to recover data for early times. Data transmitted on the fiber link are shown in Figure 18. As can be seen, the

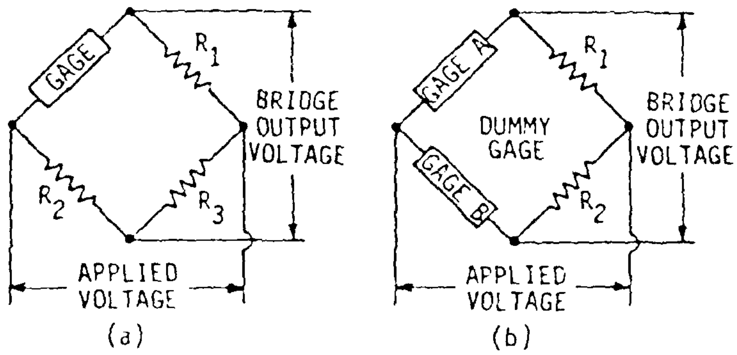

Figure 16. Typical strain gauge bridge configurations.

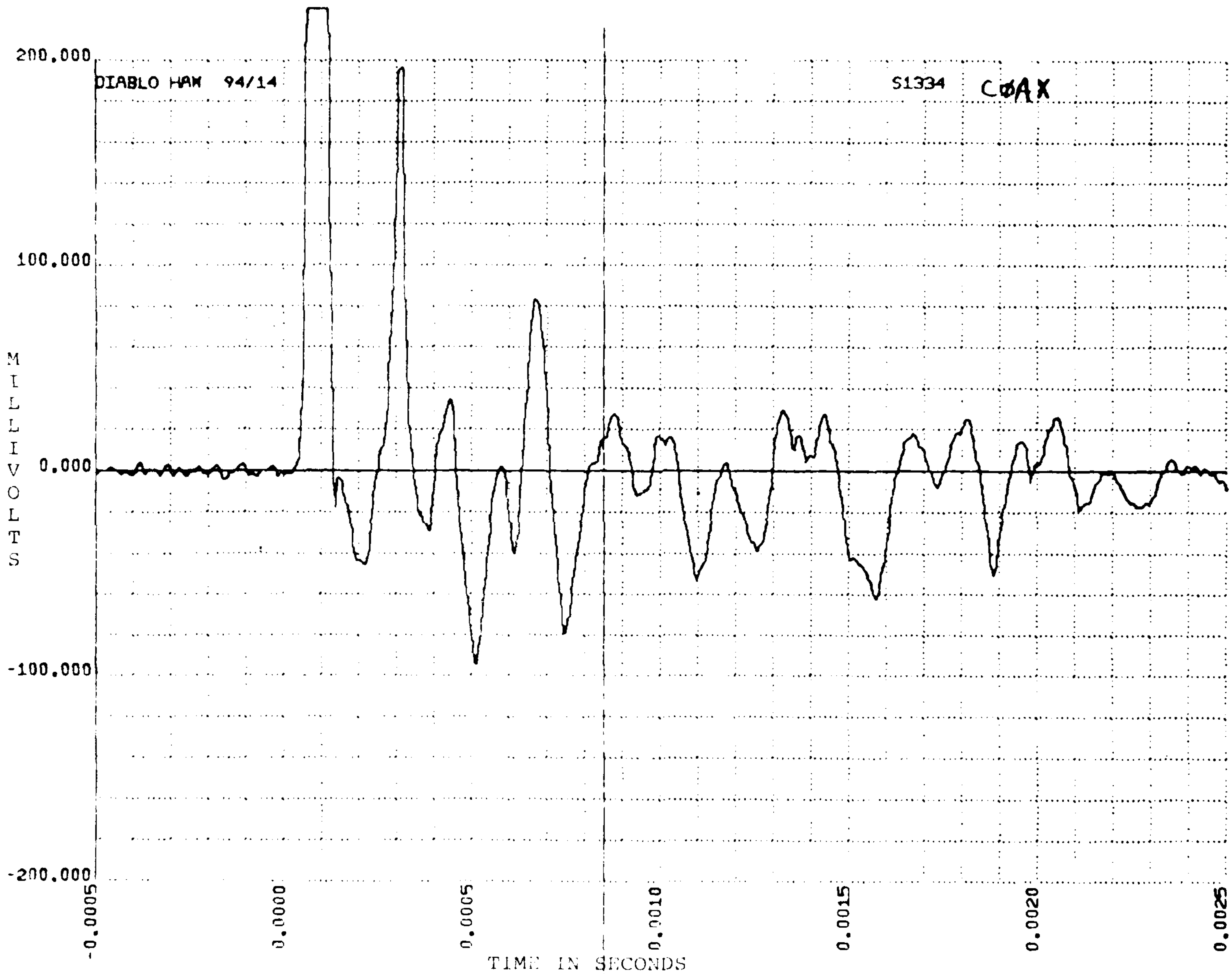

Figure 17. Strain gauge data transmitted on coaxial cable.

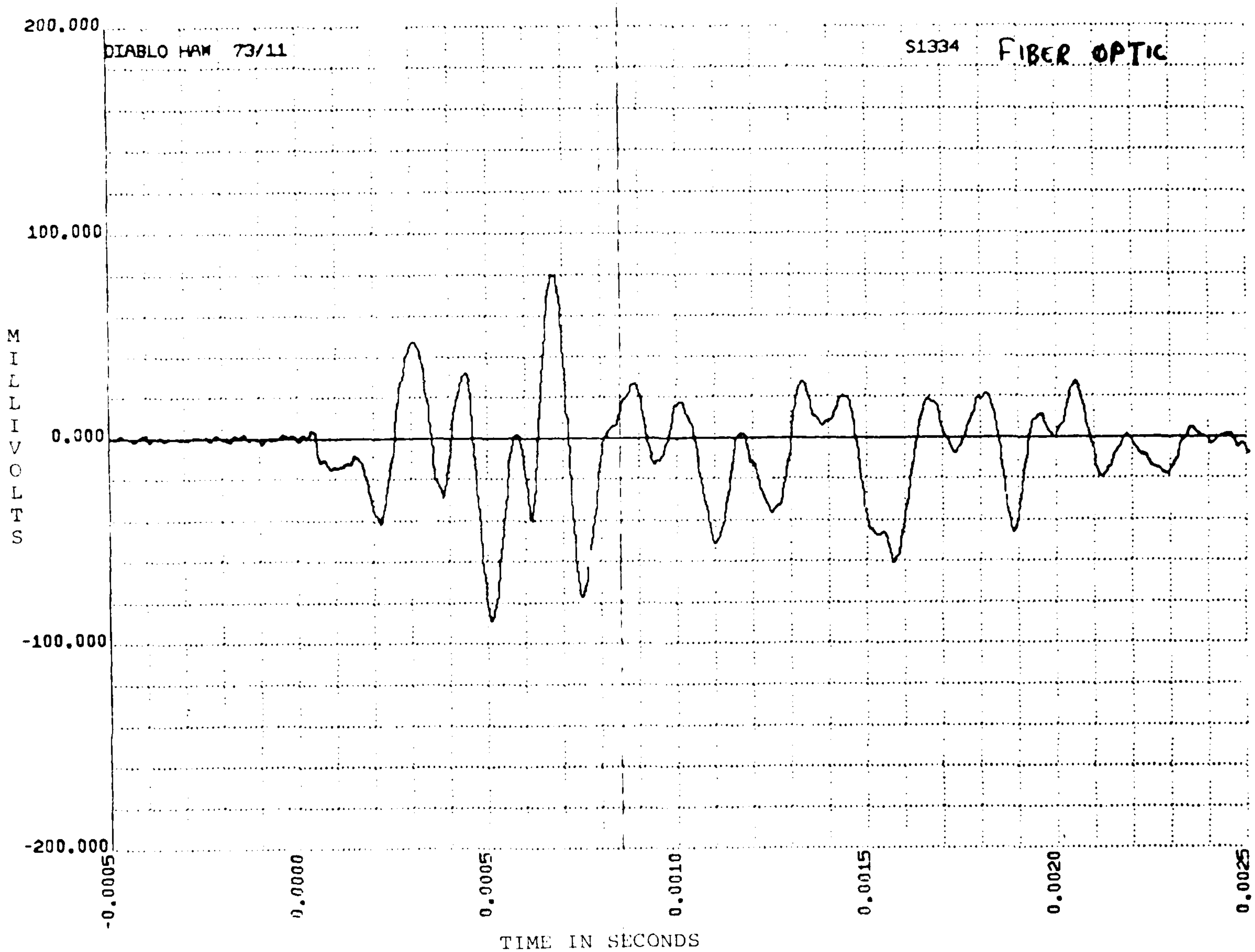

Figure 18. Strain gauge data transmitted on fiber optic cable.

dielectric link eliminated the early time noise and, therefore, provided strain gauge data for times less than 400 microseconds. These results exceeded expectations in terms of noise spike suppression and signal-to-noise ratio.

4-4. FUTURE USES OF FIBERS IN UGT.

Data transmission links utilizing fiber optics are planned for upcoming DNA-sponsored events. The results of previous work, as discussed in this report, have been very encouraging. The redundant, parallel coaxial cable transmission link will be eliminated in future events (Ref. 17). Multiplexed, digital fiber optics links have been designed and are ready for field use (Ref. 18). Current work is underway towards development of transducers which yield optical signals directly (Ref. 19). Also, fiber characterization studies in the UGT environment are continuing (Ref. 20).

SECTION 5

CONCLUSIONS AND RECOMMENDATIONS

Fiber optics can and have been used to great advantage in underground nuclear tests. The interest in fiber optics is justified by numerous advantages over metallic conductors including:

- lower costs
- elimination of cable plant ringing
- increased bandwidth
- elimination of cross talk between experiments

Experience with fiber cables at NTS indicates that their performance exceeds expectations in terms of ruggedness. Results of tests show minimal fiber degradation during and after the rough handling typical of the NTS environment.

Fiber optic research is continually undertaken in the civilian market, particularly in the communications field. While much of this work leads to results useful in all applications, the unique requirements and environment of underground nuclear tests require specialized research and development in order to capitalize on the advantages of fiber optics. In particular, the following areas should be investigated:

1) Economic and technical study to evaluate replacement of the permanent cable runs with fiber optic transmission links. The study should include evaluation of transmitters, receivers, and possible multiplexing techniques. Multiplexing possibilities are greatly enhanced due to the much greater bandwidth capabilities of optical fiber transmission systems.

2) Specifications and designs of optical links for standard gauge types: strain, impulse, etc.

3) Development of mechano-optical transducers as applicable to parameters of interest to DNA. This effort should include the application of LASL's diagnostic work with fibers to DNA events. Also, current transducer development work at the Naval Research Laboratory should be evaluated for possible DNA UGT applications.

4) Evaluation of fiber optic use for data transmission from gauge to instrumentation alcove. These studies would have to consider radiation hardening of transmitters. The advantage is in the reduction of zero time noise.

5) Fiber effects studies to provide radiation behavior data where data do not presently exist. Due to the non-linear behavior of fiber when exposed to nuclear radiation, it is extremely difficult and risky to extrapolate existing data to radiation fields of interest. In addition, consideration should be given to the possibility of utilizing photo-bleaching for annealing radiation-induced effects.

In addition to benefitting UGT, advances in fiber optic technology can greatly impact other DNA activities such as hardening of military components and simulation and testing in high radiation fields. Using the UGT environment as a test bed, optical fibers can be characterized in severe radiation and stress environments. Due to the importance of these characteristics and the potential benefits, it is recommended that DNA take a lead role in the research and development of fiber optic technology for use in adverse test and simulation environments.

SECTION 6

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DEPARTMENT OF THE NAVY (Continued)

Naval Research Laboratory
ATTN: Code 6503, J. McCallum
ATTN: Code 6584, E. Friebele
ATTN: Code 6[illegible]4, R. Allen
ATTN: Code 6503, T. Giallorenzi
ATTN: Code 65[illegible], R. Ginther
ATTN: Code 7904, B. Collins
ATTN: Code 7904, B. Evans
ATTN: Code 7904, E. Abella
ATTN: Code 7[illegible]4, G. Siegel
ATTN: Code 7909, [illegible] Garrett
ATTN: Code 7909, [illegible] Griscom
ATTN: Code [illegible]4, B. Evans
ATTN: [illegible], Dr. Revese

Naval Security Group Command
ATTN: N. Woodman

Naval Surface Weapons Center
ATTN: [illegible] Holton
ATTN: Code R1[illegible], [illegible] Hammond
ATTN: Code [illegible]14, [illegible] Blatstein
ATTN: Code [illegible]31

Naval Surface Weapons Center
ATTN: [illegible], H. Lewis
ATTN: [illegible]

Naval Weapons Center
ATTN: [illegible] Hutcheson

Naval Weapons Evaluation Facility
ATTN: [illegible]
ATTN: [illegible]

Office of Naval Research
ATTN: [illegible]

DEPARTMENT OF THE AIR FORCE

[illegible] Laboratory
ATTN: [illegible]

[illegible]
ATTN: [illegible]

[illegible]
ATTN: [illegible]
ATTN: [illegible]

[illegible]
[illegible]
[illegible]
ATTN: [illegible]

DEPARTMENT OF THE AIR FORCE (Continued)

Headquarters Space Division
Air Force Systems Command
ATTN: SKY, C. Kennedy
ATTN: YCD, R. Spray
ATTN: YCP, H. Staubs
ATTN: YCD, F. Brininstool
ATTN: YCPT, D. Bartel
ATTN: YN, J. Sweeney
ATTN: YN, A. Varisco
ATTN: YNV, J. Turnipseed
ATTN: YN, B. Brady

Rome Air Development Center
Air Force Systems Command
ATTN: ESR, A. Yang
2 cy ATTN: ESR, J. Wall

Strategic Air Command
Department of the Air Force
ATTN: E. Winger

DEPARTMENT OF ENERGY

Department of Energy
Albuquerque Operations Office
ATTN: [illegible]

OTHER GOVERNMENT AGENCY

Institute for Telecommunications Sciences
ATTN: [illegible]

DEPARTMENT OF ENERGY CONTRACTORS

Brookhaven National Laboratory
ATTN: [illegible]

[illegible], Inc.
ATTN: [illegible]

Lawrence Livermore National Lab
ATTN: [illegible]
ATTN: [illegible]
ATTN: [illegible]
ATTN: [illegible]

Los Alamos National Scientific Lab
ATTN: [illegible]
ATTN: [illegible]
ATTN: [illegible]
ATTN: [illegible]
ATTN: [illegible]
ATTN: [illegible]

[illegible] National Laboratory
ATTN: [illegible]
ATTN: [illegible]

Sandia National Laboratories
ATTN: [illegible]
ATTN: [illegible]
ATTN: [illegible]
ATTN: [illegible]
ATTN: [illegible]
ATTN: [illegible]
ATTN: [illegible]
ATTN: [illegible]
ATTN: [illegible]

DEPARTMENT OF DEFENSE CONTRACTORS

Acurex Corporation
ATTN: K. Triebes

Advanced Research & Applications Corp
ATTN: R. Armistead

Aerospace Corporation
ATTN: W. Blocker
ATTN: S. Bower
ATTN: W. Otsuki

AMPHENOL
ATTN: [illegible] Malsch

University of Arizona
ATTN: J. Burke

Artec Associates, Inc
ATTN: D. Baum

Automation Industries, Inc
ATTN: D. Moltrup

BDM Corporation
ATTN: T. Neighbors

Bell Telephone Labs
ATTN: [illegible] Fleming

Boeing Company
ATTN: R. Caldwell
ATTN: M/S 42-33, [illegible] Kennedy
ATTN: [illegible]
ATTN: [illegible]
ATTN: [illegible]
ATTN: [illegible]
ATTN: [illegible]

University of California
ATTN: [illegible]

[illegible]
ATTN: [illegible]

[illegible]
ATTN: [illegible]

[illegible]
ATTN: [illegible]
ATTN: [illegible]

[illegible]
ATTN: [illegible]

[illegible], Inc
ATTN: [illegible]
ATTN: [illegible]

[illegible]
ATTN: [illegible]

[illegible], Inc
ATTN: [illegible]
ATTN: [illegible]
ATTN: [illegible]
ATTN: [illegible]

[illegible]
ATTN: [illegible]

DEPARTMENT OF DEFENSE CONTRACTORS (Continued)

[illegible] Idaho, Inc
ATTN: [illegible]
ATTN: [illegible]

[illegible], Inc
ATTN: R. Lynn
ATTN: M. Nelson
ATTN: [illegible] Davies

[illegible], Inc
ATTN: [illegible] Cavanaro
ATTN: [illegible] Gaines

[illegible]
Civil Engineering Research Facility
University of New Mexico
ATTN: [illegible]
ATTN: N. Baum

Galileo Electro-Optics Corporation
ATTN: [illegible]
ATTN: [illegible] Owen

[illegible], Inc
ATTN: [illegible]

General Dynamics Corporation
ATTN: [illegible]

General Electric [illegible]
ATTN: [illegible]

[illegible], Inc
ATTN: [illegible]
ATTN: [illegible]
ATTN: [illegible]

[illegible]
ATTN: [illegible]

[illegible]
ATTN: [illegible]

[illegible]
ATTN: [illegible]

[illegible]
ATTN: [illegible]

[illegible]
ATTN: [illegible]

[illegible]
ATTN: [illegible]

[illegible] Institute
ATTN: [illegible]

[illegible]
ATTN: [illegible]

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[illegible]
ATTN: [illegible]
ATTN: [illegible]

[illegible]
ATTN: [illegible]

DEPARTMENT OF DEFENSE CONTRACTORS (Continued)

ITT Electro-Optical Products Division
ATTN: M. Maklad
ATTN: [illegible]
ATTN: J. Wilhelm
ATTN: A. Asam

Jaycor
ATTN: [illegible]

Jet Propulsion Laboratory
ATTN: P. Watson

Kaman—TEMPO
ATTN: DASIAC
ATTN: [illegible]

Kaman Sciences Corporation
ATTN: [illegible]
ATTN: [illegible]
ATTN: [illegible] Sachs
ATTN: [illegible] Shelton

Litton Systems, Inc
ATTN: [illegible]

Lockheed Missiles & Space Co, Inc
ATTN: [illegible]
ATTN: [illegible]
ATTN: [illegible]
ATTN: [illegible]
ATTN: [illegible]
ATTN: [illegible]

Lockheed Missiles & Space Co, Inc
ATTN: [illegible]
ATTN: [illegible]
ATTN: [illegible]
ATTN: [illegible]
ATTN: [illegible]
ATTN: [illegible]

Lockheed Missiles & Space Co, Inc
ATTN: [illegible]

Lovelace Biomedical & Environmental Research Institute, Inc
ATTN: R. Fletcher

Martin Marietta Corp
ATTN: [illegible]
ATTN: [illegible]
ATTN: Tech Library

McDonnell Douglas Corp
ATTN: [illegible]
ATTN: M. Campbell

McDonnell Douglas Corp
ATTN: [illegible]
ATTN: [illegible] Campbell
ATTN: [illegible]

University of Michigan
ATTN: [illegible]

Mission Research Corp
ATTN: [illegible]
ATTN: [illegible]

Newport News Shipbuilding
ATTN: [illegible]

DEPARTMENT OF DEFENSE CONTRACTORS (Continued)

Mitre Corp
ATTN: B. Metcalf
ATTN: [illegible] Quarato

Nichols Research Corp, Inc
ATTN: N. Byrn

Northrop Corp
ATTN: [illegible]
ATTN: A. Kalisa

Pacific-Sierra Research Corp
ATTN: H. Brode

Physics Applications, Inc
ATTN: C. Vincent

Physics International Co
ATTN: [illegible] Moore
ATTN: Technical Library

Polytechnic Institute of New York
ATTN: A. Oliner

R&D Associates
ATTN: W. Graham
ATTN: [illegible]
ATTN: [illegible]

Rockwell International Corp
ATTN: [illegible]
ATTN: [illegible]
ATTN: [illegible]

University of [illegible]
ATTN: [illegible]

Science Applications, Inc
ATTN: [illegible] Miller

Science Applications, Inc
ATTN: Technical Library

Science Applications, Inc
ATTN: W. [illegible]
ATTN: Tech Library

Science Applications, Inc
ATTN: W. [illegible]

Science Applications, Inc
ATTN: [illegible]

DEPARTMENT OF DEFENSE CONTRACTORS (Continued)

Southeastern Institute of Technology
ATTN: E. Watson

Spectronics, Inc
ATTN: I. Stewart

Sperry [illegible]
ATTN: [illegible], W. Davis

SRI International
ATTN: J. Abrahamson
ATTN: [illegible] Lee
ATTN: [illegible]

Sylvania Systems Group
ATTN: [illegible] Waldron

Systems, Science & Software, Inc
ATTN: [illegible] Grine
ATTN: P. Coleman

Teledyne Brown Engineering
ATTN: D. Henderson
ATTN: [illegible] Landwehr

Tetra Tech, Inc
ATTN: [illegible] Hodara

Times Wire and Cable Co
ATTN: W. Primrose

TRW Defense & Space Sys Group
ATTN: [illegible] Gaar
ATTN: N. Lipner
ATTN: [illegible]
ATTN: [illegible] Eastman
ATTN: [illegible] Armstrong
ATTN: A. Thomas
ATTN: [illegible]
ATTN: [illegible]
ATTN: [illegible] Walter, MS [illegible]
ATTN: [illegible]

TRW Defense & Space Sys Group
ATTN: [illegible]

Waltec Corp
ATTN: [illegible] Aggarwal

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